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HYPERVELOCITY PROJECTILE TECHNOLOGY (D2)

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Abstract

The D2 hypervelocity projectile program is sponsored by the Strategic Defense Initiative Organization (SDIO), United States Army Strategic Defense Command (USASDC), and United States Army Armament Research, Development and Engineering Center (ARDEC). The prime contractor is GE Aerospace. The D2 projectile is targeted against ICBMs, SLBMs and SRBMs and will be launched from an Electro-Magnetic (EM) Gun. The D2 projectile is also a candidate for TMD missions. Several key technology advances have been made in the seeker, propulsion, inertial measurement and structural subsystem areas. These advances push the state of the art in performance, miniaturization, and gun G-hardening. This paper outlines the projectile system concept and the extensive technology development testing to date.

Concept Overview

The following is a brief description of the D2 projectile and it's subsystems. A more detailed description of the critical subsystems and components will follow in the section on technology advances.

The design of the D2 projectile (Figure 1) was driven by the severe environments associated with the electromagnetic launcher and with operating in a hypervelocity regime. The basic shape is a three (3) degree half-cone with a 5.8 mm nose radius. In order to increase stability at launch, an additional six (6) degree flare was added to the aft end of the airframe, beginning at about 58.2 mm from the rear and continuing back. This gives the projectile a static margin of approximately 3%, which is sufficient to compensate for 3 radians/sec of tip-off, until the control system is activated. High static margins are not desired, because of the adverse effect on projectile maneuvering. In reality, the static margin of the projectile will be decreasing as the nosetip recesses and the center of gravity and center of pressure shift. Eventually, the static margin will be negative and the projectile will be flying marginally unstable. This is desirable, because of the maneuvering benefits it imparts of the system.

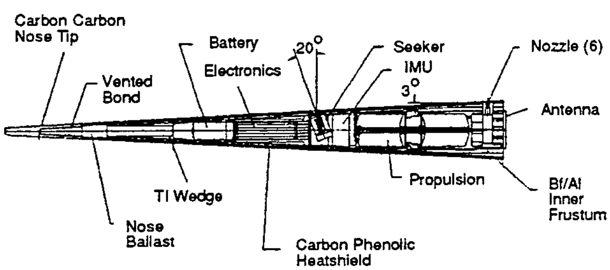

Figure 1. The D2 Hypervelocity Projectile

In order to perform engagements beyond 50 km, a launch velocity of 4 km/sec is required. This puts an enormous thermal burden on the airframe. To compensate for this, the front portion of the nosetip of the projectile is made of 3-D carbon-carbon. the nosetip is designed for controllable recession, under the most stressing weather conditions and engagement trajectories. Thermal protection for the airframe is performed using a carbon phenolic heatshield, similar to those used on ballistic reentry vehicles. This heatshield will protect the projectile components for the duration of the most stressing trajectory.

In order to reduce the barrel length requirement on the launcher, a maximum barrel length requirement was set at 12 meters. From this, the derived peak acceleration is 100,000 Gs.

It is for this reason that the airframe, sabot and all components of the projectile were designed to withstand this peak launch acceleration. Aside from the fact that the reduction of weight was key to survivability and reducing launcher power requirements, standard materials did not lead to a viable design. These materials either could not withstand the launch environment, or produced designs that were beyond weight and packaging goals. The solution to this problem was the expanding field of composite materials, combined with innovative design techniques. A complete description of the structures will come later in this paper.

Lethality is always an issue. Because of the very high closing velocities involved when intercepting a reentry vehicle (5-8 km/sec), it was derived that a kinetic energy intercept would be sufficient to insure a kill. This simplified the system by eliminating the need for an onboard warhead, but at the same time, increased the accuracy requirements. A command guided, hit-to-kill interceptor that needs to be effective at such long ranges puts an unrealistic tracking accuracy requirement (< 50 microradians) on the fire control system. Because miss distance increases with range for a fixed sensor error, long range intercepts require very accurate fire control sensor measurements. Additionally, because of an all weather operation requirement and the effects of the atmosphere on the fire control tracking accuracy, the specifications for an operational, extended range, command guidance fire control were considered beyond the state of the art of current fire control development efforts.

The decision was then made to develop a "dual mode" projectile that could operate effectively and inexpensively in the close range and extended range mission scenarios (Figure 2). Up to a "transition" range, the projectile can operate in a strictly command guided mode for close-in engagements. In the command guided mode, a command receiver, on-board the projectile, receives pitch and yaw acceleration commands from the ground based fire control platform and issues these command to the projectile autopilot. The autopilot uses pitch, yaw and roll rate gyro outputs to damp the projectile body rates and uses pitch and yaw accelerometer outputs as references to follow commands. The autopilot then issues thrust commands to the control subsystem.

For intercepts beyond the transition range, the projectile initiates a terminal homing mode of operation. The fire control will still command the projectile, but only into an acquisition basket. Once in the basket, the projectile will be given an orientation command to locate the target within the field of view (FOV) of an on-board seeker.

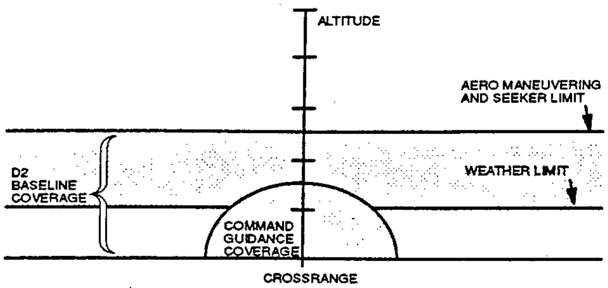

Figure 2. D2 Engagement Envelope

The projectile will take over when the seeker acquires the target. In the homing guidance mode, a nine (9) state Kalman filter receives seeker measured target line-of-sight data and inertial measurement unit (IMU) incremental velocity and angle data and estimates the target acceleration and the projectile/target velocity and position.

The feature of the D2 projectile that enables it to operate beyond the range of command guidance only projectiles is its optical seeker. This on-board sensor uses established focal plane array (FPA) and optical technologies to afford a lightweight, uncooled, subsystem to replace a breakthrough in ground based fire control sensor technology. Because the seeker FOV of 15 x 15 degrees is pointing 70 degrees off the center axis of the projectile, the engagement trajectory must be "shaped" to keep the target in the FOV during acquisition and tracking. The need for a side looking seeker is due to the degraded performance and cooling requirements caused by the heating effects of the atmosphere on nose mounted seeker windows. The seeker subsystem and engagement trajectories will be described in greater detail later in this paper.

Flight scenarios to all regions of the engagement envelope and target maneuverability capabilities determined the requirements of the projectile, as well as the subsystem response time, thrust, total impulse and flight duration requirements of the control subsystem. The most stressing engagement revealed the need for a maximum of 10 Gs of maneuverability, a maximum flight duration of 22 seconds with 765 N-sec of total impulse, a maximum thrust level of 86.7 N and a minimum response time of 2 msec. To meet these requirements, a liquid bi-propellant control subsystem was chosen, with an aft located, six (6) nozzle configuration. The control subsystem will also be described in greater detail in this paper.

While it is true that command guidance with terminal homing relaxes the fire control sensor measurement accuracy requirement, this is at the expense of the on-board seeker and an accurate IMU. Because of the long flyout times and the fact that the projectile uses a body fixed seeker, the most stressing IMU performance requirements are derived from the terminal homing phase of the engagements. A less obvious, but equally stressing requirement, is the IMU packaging. Because of the extremely severe environment of the electromagnetic launcher "G-hardness" of the IMU components is critical. This not only means surviving the gun launch, but also maintaining the strict performance specifications for the flyout that follows. Because of space limitations, the IMU and electronics development will not be described in this paper.

Because miniaturization is critical to meeting size and weight specifications, the electronics design uses a hybrid packaging approach known as High Density Interconnect (HDI) developed by GE-CR&D (Corporate Research and Development). The approach uses polymer layer interconnection overlays laminated over bare chips mounted on a substrate. HDI major advantages are packaging density (2 mil pitch), heat dissipation capabilities, and the fact that overlays can be removed and replaced without chip damage.

<u>Technology Advances – Aero Optics</u>

In order to overcome the range limitations of ground based fire control systems, a solution was needed that would not degrade in performance as the range from the fire control installation increased. An on-board terminal homing seeker was chosen because of it's independence from fire control. In fact, terminal homing seekers generally become more accurate as they close in on the target, because the angular error decreases as the relative distance decreases. The D2 seeker concept developed by GE Aerospace uses an innovative design, while remaining relatively simple.

The concept being developed (Figure 3) is a strapdown seeker with a boresight angle of 70 degrees off axis. The total allowable angular error requirement is 150 microradians. The unit is recessed in a 12 mm diameter by 6 mm deep cavity, giving it a field of view (FOV) of 15 degrees x 15 degrees. The focal plane array (FPA) is a silicon charge injection device (CID) with a 512 x 512 array of pixels. These pixels are randomly accessed to operate at a readout rate of 500 Hz. The optics are comprised of a singlet lens to project the image on the FPA and a sapphire window, to protect the seeker from the thermal environment.

The FPA selection was driven by two issues: pixel saturation (blooming response) and read-out architecture. Because the target signal in the late end-game is orders of magnitude higher than during target acquisition, the tracking algorithm performance would be degraded if this excess signal

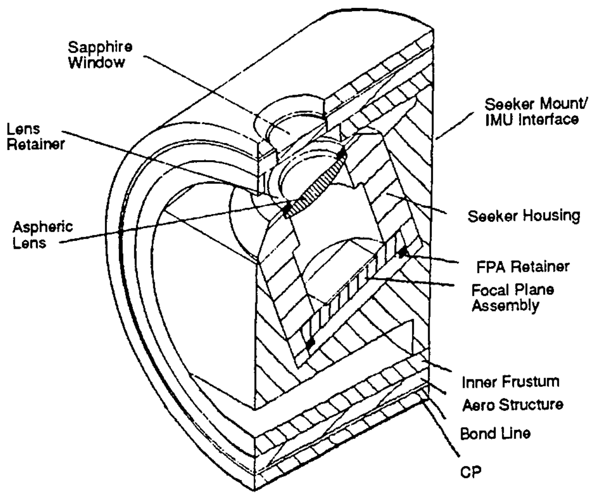

Figure 3. Seeker Concept

formed a symmetric pattern on the FPA. This effect is known as blooming and is due to excessive signal that "bleeds" into neighboring pixels. Charge injection devices (CIDs) are far more bloom resistant than charge coupling devices (CCDs).

The read-out architecture is an issue because the large field of view and high resolution requirement indicates the use of a 512 x 512 pixel array. In order to reduce the processing time, only a 32 x 32 pixel array will be read out at any time during acquisition and only a 16 x 16 pixel array during tracking. This assumes that the fire control will tell the interceptor the relative target location to within a 2 x 2 degree window. Because of this random access read-out requirement, CID technology was chosen. Even without sensor cooling, the temperature of the FPA will only range from +5 C to +55 C. Because of this requirement silicon was chosen as the best detector material to operate under these conditions.

The aero environment that the projectile will operate in is not only driven by the interceptor velocity, weather conditions and altitude, but also by the angle of attack made by the interceptor during a maneuver. This environment effects the seeker by producing a refracted target image on the FPA, thus providing erroneous data for interceptor trajectory corrections. The refraction is caused by two major sources: airflow in and around the seeker cavity and seeker window heating.

During the terminal homing portion of the interceptor flyout, a potentially turbulent boundary layer is formed around the area of the cavity. The accuracy of the optical system is dependent on predicting this environment.

To quantify the magnitude of the thermal environment and the aero-optical refraction, computational fluid dynamics (CFD) and aero-optical ray tracing simulations were done for worst case flyout trajectories. Cases were run with both laminar and turbulent flow to determine the effects of both conditions. To validate these codes, three (3) series of tests were set up for the Aero Optical Evaluation Center (AOEC) shock tunnel facility at Calspan in Buffalo, NY.

The first series will take a full size model of the D2 airframe and instrument in and around the seeker cavity with pressure and heat transfer gages. This data will be used to confirm full Navier–Stokes predictions for turbulent cavity flow.

The second test will model the seeker aperture to assess the noise and refraction environment in the cavity. The model will be instrumented with a quad detector, attached to a vibration isolation system, to eliminate tunnel noise from refraction measurements.

The pre and post test analyses for this testing will use Teledyne Brown Engineering (TBE) AOQ code for optical performance.

The final test series will take the D2 seeker (FPA, optics, breadboard electronics) into the tunnel to quantify the performance of the seeker subsystem.

<u>Control Subsystem</u>

The nature of the threat being designed to, dictated that the interceptor have an exceptionally rapid response in it's maneuvers as well as sufficient control for an extended flight time. When combined with the launch survivability requirements and volume limitations, a revolutionary propulsion subsystem was needed. The critical requirements being put on the control subsystem are listed below:

Response time: 2 msec (signal to 90% thrust)
Total impulse: 765 N-sec
Launch Acceleration: 100,000 Gs
Packaging envelope: 50.8 mm min. diameter
(conic cylinder) 68.6 mm max. diameter,
0.22 m length

The control subsystem for the D2 projectile is a jet reaction control system (JRCS) being developed by the Aerojet Propulsion Division. The baseline design (Figures 4 and 5) is a liquid bi-propellant system that provides two 86.7 N thrusters in the yaw axis and four 43.4 N thrusters in the pitch/roll axis. The two separate propellant tanks are pressurized by a solid gas generator that acts on bonded rolling diaphragms inside the tanks to expel the fuel and oxidizer. The thrust is controlled by solenoid actuated valves which not only control the thrust direction, but can regulate the thrust level to either 40% or 100%. This allows for a more efficient guidance scheme.

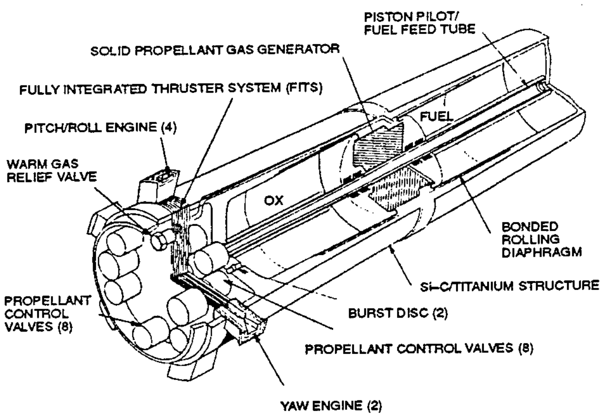

Figure 4. JRCS Concept

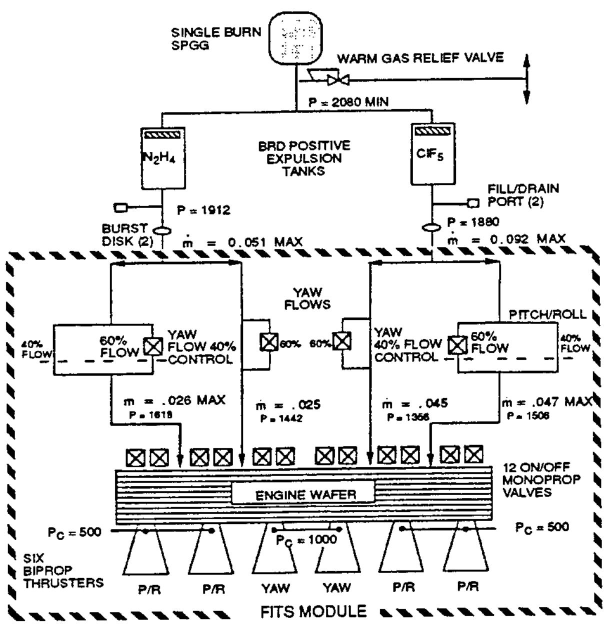

Figure 5. JRCS Schematic

In order to meet the total impulse requirement and still fit the volumetric constraints, a high I_{sp} system was needed. Solid and liquid propellants were all considered. Solids and liquid monopropellants were both eliminated because they could not meet the total impulse requirements within the packaging envelope. Because it met the impulse requirement and was already being developed on other SDIO and Air Force sponsored programs, Aerojet chose chlorine-pentafloride (ClF_5) as the oxidizer and hydrazine (N_2H_4) as the fuel in a liquid bi-propellant system. The ClF_5/N_2H_4 mixture has an I_{sp} of 275 sec, which will deliver a total impulse of 765 N-sec in the D2 system.

To meet the response time requirement, small, lightweight solenoid valves were developed by Aerojet and their subcontractor, Moog. The issue was not just meeting the response time specification, but doing so within a peak valve power of 21 watts. The power requirement has been relaxed to 27 W peak with a 1.1 A current limit. The requirement change will not significantly impact battery size. The original Moog valve design, which met the packaging requirements, was fabricated and hot fire tested in a single thruster configuration in 1990. The results revealed that thrust levels and specific impulses were within expected values, the thrust was with peak power requirements and the thruster would be chug stable at 40% thrust. Unfortunately, the thruster response times were between 3 and 5 msec. With the exception of approximately 0.7 msec for line losses, this time was due to the response of the valve.

In order to meet the 1.3 msec requirement on the valve, Moog made a number of configuration and material changes. The first change was in the geometry of the valve armature. The original design was conic in shape, which was trapping the propellant and increasing the opening and closing time of the poppet. The revised armature design was a flattened top, with passages drilled axially, to allow the fluid more area to flow through.

The second modification was to increase armature force by improving the magnetic properties. This was done two ways. First, nonworking airgaps in the current flux path were eliminated by replacing the air voids with a magnetic material. Secondly, the armature material was changed from a silicon iron alloy to vanadium permendur, which is an iron cobalt alloy. This material, while having better magnetic properties than 2.5% SiFe, has never been tested for compatibility with CLF_5. Prior to finalizing the design change, permendur valves were immersed in the oxidizer for an extended duration, with no degradation in the material.

The combination of these changes led to valve opening and closing response times in the 1.2–1.3 msec range in cold flow testing with flight propellants.

Rather than retest these valves in a single thruster configuration, it was decided to fabricate and test the full size FITS platelet stack, with all six thruster ports machined out. This development itself was a major accomplishment because of the small orifices, passageways, and injectors that were needed, as well as the intricacy of the nozzle geometry.

In order to capitalize on jet interaction effects, all six nozzles were canted at a 20° forward angle. Furthermore, the pitch/roll valves had an additional bend of 35° to the side. This required several iterations in machining the chamber liners because of the double angle and strict tolerances.

As a first test series of the FITS, only one pitch/roll engine would be tested at a time. All other nozzles and valve opens will be capped. During this test series with the flight propellants, thruster response time will be measured, as well as power consumption, mixture ratio, engine temperature, and chamber pressure. The tests that will be run will vary the number of pulses, pulse, and coast widths, and will be run at 40% and 100% thrust. The next step in the FITS development will be to fabricate the yaw valves and incorporate them into a full FITS test.

Airframe and Sabot

The environment of the electromagnetic launcher is a harsh one, to say the least. The advantage of the EM launcher is that it not only can accelerate the interceptor quickly, but it can sustain that acceleration as the projectile travels down the barrel. This is dissimilar to conventional power guns, where the acceleration exponentially decays immediately following the peak. Because the EM launcher can sustain this acceleration, the gain in muzzle velocity is a considerable. As stated previously, a peak acceleration requirement of 100,000 Gs was established for terminal defense missions.

This requirement made it impractical to use conventional materials in the airframe and sabot designs. Materials with high strength to density ratios were needed. High strength, because of the severe launch loads imposed by the gun. Low density is desired in order to lower the launch energy requirement as well as maximizing the internal packaging volume. Because tensile and lateral loads are an order of magnitude lower than the compressive loads, unidirectional, fiber-reinforced composite materials were regarded as having the most promise. The matrix material would need to be chosen to compensate for the tensile and lateral loads.

Because the D2 projectile (Figure 1) is subcaliber to the gun bore and cannot survive the dynamic gun environment unprotected, a sabot will be used. The sabot will be used to provide lateral support to the projectile during launch, as well as add shielding against the magnetic environment of the EM launcher. The sabot, which will discard upon exiting the muzzle, is a six petal concept that uses inverted cones, with intermediate plugs and bore riders, to provide the lateral support.

A materials test program, similar to the one done for B/Al, was performed using the sabot material, uniaxial graphite epoxy composite (Gr/Ep). A number of Gr/Ep varieties were tested and AS4G/E773FR yielded the highest brooming allowables, approximately 115 ksi. This value was used as a design allowable in the sabot design.

Currently, the only available EM launchers with reasonable launch energies are in the 90 mm bore diameter size. For this reason, a scaled, 90 mm version of the prototype airframe and sabot was designed. Known as a breadboard version, this was designed as a near-term test vehicle to be fired in one of these existing EM launchers. However, before firing in the EM launcher, the design needed to be validated under similar loads in a powder gun.

SPARTA was subcontracted to concurrently fabricate the B/Al airframes, Gr/Ep sabots, and a Gr/Ep demonstrator airframe. Since the B/Al airframe and the Gr/Ep sabot were both high risk designs, this demonstrator airframe would be used to validate the sabot design in the powder gun, prior to testing the B/Al airframe. This demonstrator airframe was designed with a sufficient factor of safety to temporarily reduce the risk in the airframe design, so that the sabot concept could be demonstrated as a separate unit.

Because of the conic shape of the projectile and the fact that is would eventually be fabricated with a carbon-phenolic heatshield that needed to be designed with minimal surface irregularities (because of the high thermal loads), the original D2 sabot design (Figure 6) was based on a base push concept. Because there are no attachment points between the projectile and sabot, there will be no axial load transfer between the two. The inverted cone sabot concept was chosen for its low weight and high stiffness potential. Solid plugs are located inside the cones at the locations of the bore riders to transfer the lateral loads inbore.

Each sabot petal was fabricated as a number of separate Gr/Ep pieces: the inner petal, the outer tube, two internal plugs, and the front face cap. The inner petal, which conforms to the outer surface of the projectile, was fabricated by laying up Gr/Ep plies on a male mandrel having the projectile's outer dimensions. The directions of the fibers in this part were a combination of 0° and ±15°. The part is then consolidated, or compressed, which bleeds out excess resin and brings the part to its final thickness. The outer cone was fabricated similarly, with 0° and ±15° fiber layups, except that the part was consolidated as a complete cone around the entire circumference of the inner mandrel. These two parts are

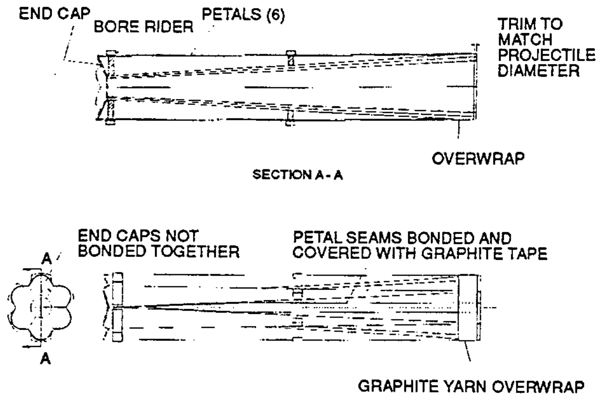

Figure 6. Breadboard Sabot Assembly

then consolidated together in a separate tool, using 0° Gr/Ep tape strips at the seams.

The solid plugs and front caps were fabricated by laying up alternating 0°, ±45°, and 90° Gr/Ep plies and consolidating them in sheets to the desired thickness. The plugs and caps were then punched out from the sheets to their final dimensions. The next step in the assembly process was to insert and epoxy bond the plugs inside the conic tubes and bond the front cap onto the top of the tube. The final step was to bond polypropylux bore riders onto the tubes at the locations of the plugs.

As soon as the Gr/Ep sabot petals and demonstration projectile were completed, they were assembled together and integrated with a titanium thruster plate and polypropylux base obturator. Two units were tested at the Terminal Effects Research and Analysis (TERA) test facility at New Mexico Tech in a modified powder gun. The gun was fabricated from two 90 mm, M–41 gun tubes, jointed end-to-end, with the rifling honed out.

Shot no. 1 was at 70,000 G axial acceleration and 1.9 km/s muzzle velocity. X-rays did not trigger properly on this shot. Streak photography showed that the leading edges of these petals were damaged inbore. The caps and plugs were visible, separate from the petals, and the tube walls were splintering. The projectile exited the muzzle intact; but because of the petal damage inbore, proper separation did not occur. These photos, along with recovered hardware, lead to the preliminary, on-site conclusion that one or more of the bore riders were sheared off inbore. This caused a large balloting force on the front of the sabot, and the petals were damaged prior to muzzle exit.

Since the bore riders had a relatively small surface area and were only held onto the petals with epoxy, it was decided to modify the remaining round, on-site, and duplicate the conditions of shot no. 1. This modification was to machine off the existing bore riders and replace them with longer strips of fiberglass tape, providing approximately five times more shear area than with the original design.

Unfortunately, this modification turned out to be a moot point because when the second shot was fired, an erratic primer caused spikes in the pressure pulse and the airframe/sabot broke up inbore. The peak axial acceleration was 85,000 Gs; but because of the short rise time and the spiked profile, an amplified and cyclic load was placed on the round. This was considered a nonstandard acceleration pulse and an environment for which the round was not designed.

Following the first test series, a detailed failure analysis was done on the sabot and projectile. A finite element analysis in the area of the bore riders confirmed the marginal bond strength of the polypropylux bore riders to the petals. In response to this analysis, a modification was made to the petal design. The bore riders were to be fabricated as an integral part of the petal. The bore rider material was changed to Gr/Ep and was laid up and consolidated with the petal, eliminating the bond failure mode. This design increased the surface area, as well as the shear strength of the bore rider.

An additional analysis was made of the gun environment. After a re-examination of the free stream shock impingement conditions, a ram pressure of 1200 psi was discovered on the front face of the petal. This is an amplification factor of four over that used in the baseline design. This increased pressure was then used in the stress analysis. The analysis revealed a failure mode where the petal and cap debonds from the tube because of cap bending. Four complete sets of petals, along with four demonstration projectiles were fabricated for a second test series at the TERA facility. The difference in configuration for test series no. 1 and test series no. 2 is shown in Figure 7.

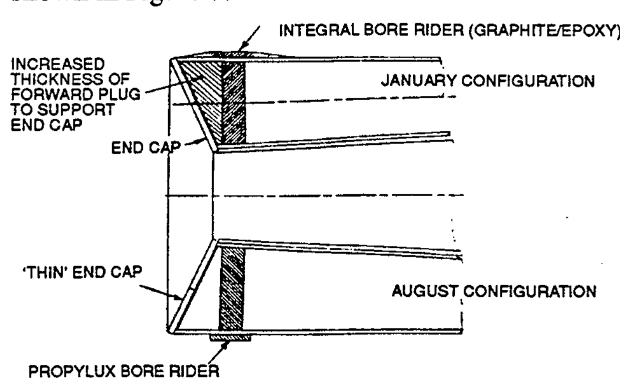

Figure 7. Design Modifications (Post August Test) 1200 psi Cap Pressure

Shot no. 1 was at 50,000 G axial acceleration and 1.71 km/s muzzle velocity. Again, muzzle x-rays failed to trigger, so the integrity of the sabot at the muzzle was not positively known. Streak photos did show the projectile intact, but also showed the sabot petal tubes were breaking up. Without the x-rays, it was unknown whether this occurred inbore or after muzzle exit.

After doing a slug shot to ensure that all test instrumentation was working, it was decided to follow the test plan and fire the next round. Shot no. 2 was at 60,000 G axial acceleration and 1.97 km/sec muzzle velocity. Again, streak photos showed the projectile to be intact, but also showed the sabot petal tubes were breaking up. Fortunately, muzzle x-rays were obtained. They showed that at least two of the front caps were debonding, the forward plugs were moving aft, and the tubes were starting to collapse. This occurred late in the travel down the barrel, so the projectile remained intact; but the fact that the petals were damaged during the separation process caused an initial yaw in the projectile.

From this data and the down-bore camera footage, it was concluded that the petal failure was occurring during the final portion of the gun barrel. The failure mode was, therefore, not acceleration-related, since peak acceleration occurs very early in the barrel travel and decreases exponentially as the round travels down the barrel. Velocity, on the other hand, increases as the round travels down the barrel and is at its peak at the muzzle. Additionally, as the velocity increases, the ram pressure on the front caps and tubes also increases. Therefore, the most likely failure modes as a result of this pressure were stresses beyond the material capabilities in the cap bond and in the tube walls.

Since modifications could not be made to address the velocity-related failure mode on the two remaining rounds, it was decided to tailor the next propellant charge to keep the velocity the same, but to increase the axial acceleration to determine if there was an acceleration-related failure mode in the design. Shot no. 3 was at 70,000 G axial acceleration and 2.01 km/s muzzle velocity.

Muzzle x-rays showed significant petal breakup inbore, to the point that the projectile nose tip was riding along the gun bore. The down-bore camera showed that this failure occurred earlier in the barrel travel than the two previous shots, but it was uncertain whether the failure was acceleration or velocity related.

For the last shot, it was decided to obtain further data on the velocity-related failure mode by repeating the conditions of shot no. 2. Shot no. 4 was done at an axial acceleration of 60,000 Gs and 1.97 km/s muzzle velocity. The x-rays showed the front caps on the petals were debonding, and the tubes were starting to collapse. Again, this occurred late in the travel down the barrel, so the projectile remained intact but received a tipoff force from an anomalous sabot separation. Streak photos and down-bore film were not obtained because of a delay in primer ignition.

From the test data gained during the second test series, four design modifications in the sabot were made. The first modification was to address the front cap debonding failure. In order to eliminate the reliance on the bond and a ply delamination concern, the cap had to be mechanically keyed into the tube structure. Because of the complex shape required to do this, the cap material was changed from Gr/Ep to 7075–T6 Aluminum. This met the strength requirements, had a minimal weight impact (14 g versus 16 g), and allowed the complex geometry to be fabricated cheaper and easier than the Gr/Ep. The new cap had a shoulder that seated itself on the sabot tube to prevent axial movement, while an inner cylinder slipped inside the tube to prevent lateral movement. One other benefit was the increased radial stiffness and hoop strength it gave to the front end of the sabot tube.

The second modification addressed the tube collapse failure mode. If the assumption is made that the front cap failure was not the cause of the tube collapsing, it can be inferred that the tube was being collapsed from the outside by external pressure. The two sources of this pressure are the ram air pressure and propellant gases that pass the obturator (blow-by). Combining moderate obturator gaps with ram air pressure, an analysis of the gun environment yielded a worst case pressure of 2000 psi. Finite element analysis indicated the current design had a capability of approximately 800 psi. By changing the layup angles of certain plies in the tube, this capability could be greatly improved. After three iterations, the old ply configuration of ($0_3 \pm 15\ 0_3$) over the entire length of the tube was changed to a combination of ±75°, ±15°, and 0°, depending on the axial location on the tube. This increased the pressure capability to approximately 3200 psi.

The third modification came about after making an assumption that the bond between the sabot segments fails. This introduces a buckling failure mode near the aft end of the projectile. To compensate for this, a third bore rider was added to the petal in this area.

The fourth and final modification addressed the possibility of a brooming failure at the base of the petal. Since the evidence from the third test did not show a conclusive failure mode, it was felt that an increase in the brooming capability would be prudent. To do this, the aft end layup was altered from 33 plies to 40 plies, which equated to a thickness change from 4.3 mm to 5.3 mm.

After the analysis on all four modifications was completed, SPARTA made the necessary tooling changes and began fabrication of four sets of sabot petals and four demonstrator projectiles. The final round configuration for test series no. 3, with design modifications, is shown in Figure 8.

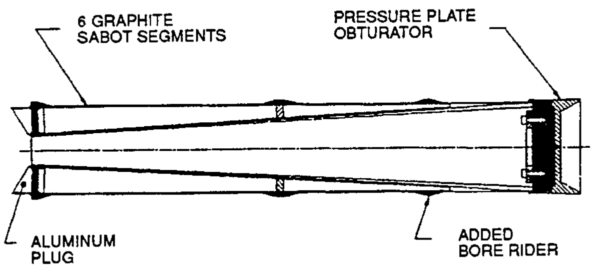

Figure 8. Breadboard Sabot

Shot no. 1 of the third test series was done at 55,000 G axial acceleration and 1.87 km/s muzzle velocity. X-rays at the muzzle showed a flawless gun launch of the projectile and sabot package. The streak photo at 5 m downrange showed the petals beginning to peel back. The streak at 11 m downrange revealed that the petals were completely away from the projectile, but were beginning to break near the aft end. The streak photo at 20 m downrange showed the further breakup of the petals, and the projectile yawed at an upward angle. This was thought to be due to a tipoff imparted by one or more of the petals during sabot separation. The down-bore camera showed symmetric petal separation, but did not reveal any further information as to the cause of the tipoff.

Specifying the exact cause of the tipoff would be difficult. The projectile being used was a hollow cone, with a static margin of only 2% and low moments of inertia, and could be easily redirected. Since the thrust plate design has a groove that radially confines the petals and airframe at the aft end and this was the pivot point during separation, it was felt that this confinement was holding the petals in contact with the airframe too long. This groove, which was 150 mils in height, was originally included in the design for an increase in the brooming capabilities at the aft end of the projectile and sabot. To establish the sensitivity of this groove height, the next round was modified at the test site to reduce the groove to a height of only 25 mils.

Shot no. 2 was done at an axial acceleration of 66,000 Gs and a muzzle velocity of 2.05 km/s. As in shot no. 1, x-rays showed the round intact at muzzle exit. No data was received from the 5 m streak camera, but the down-bore camera and the streak camera at 11 m downrange showed complete and symmetric petal separation at this point. Figure 9 shows a streak camera photo located 11 meters downrange of the muzzle. This streak photo also showed that at least two of the petals were still bending due to the aerodynamic forces, but this time it was near the midsection of the petal. The streak photo at 20 m downrange did not reveal any appreciable tipoff, and this was substantiated by the yaw card.

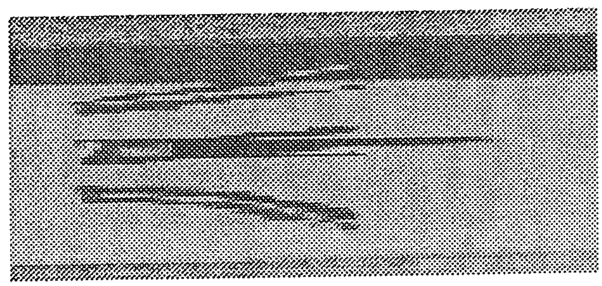

Figure 9. 11 Meter Downrange Streak Photo

It was felt that the bending of the petals in flight was not adversely influencing the projectile, since the petals were already away from the airframe when they started to bend. It was also concluded that the major contributor to the bending was not the radial constraint of the groove, but the fact that the aerodynamic forces acting axially on the petal were causing the petal to buckle against the thrust plate.

The test series was continued for shot no. 3 with an axial acceleration of 78,000 Gs and a muzzle velocity of 1.89 km/s. X-rays showed a complete breakup of the round inbore. Using timing marks on the down-bore film, it was determined that the failure occurred early, at or near peak acceleration. A detailed failure analysis is currently underway.

For the final test shot, it was decided to fire at an acceleration level in between the successful shot at 66,000 Gs and the failure at 78,000 Gs. The propellant charge was made for an estimated axial acceleration of 70,000 Gs and a muzzle velocity of 2 km/s. An abnormal propellant burn only allowed for an acceleration on shot no. 4 of 60,000 Gs and a muzzle velocity of 1.58 km/s. The streak photos from this shot showed a separation similar to shot no. 2, with little or no observable projectile tipoff.

For future shots, the interaction between the projectile and the sabot petals can be greatly reduced or eliminated by adding a tipping ring to the thrust plate. This will allow the petals to pivot off the thrust plate alone and not off the projectile base. The out-of-bore bending of the petals is something that will require further investigation. Because of the high aerodynamic forces involved, it may not be possible to move the thrust plate away from the petals before this bending can occur. On the other hand, it does not appear that there is an adverse effect on the projectile because of this, so it may not be necessary to address this issue further.

Conclusion

Terminal defense missions require fast and accurate interceptors to meet current and future threats. The environment of the electromagnetic launcher also imposes some strict size, weight and structural requirements on the interceptor components and subsystems. The D2 program has already demonstrated leaps in technology in the areas of uncooled optical seekers, miniature control systems and IMUs, and composite structures. Future work will further advance these and other technologies and ultimately lead to flight qualified subsystems ready to be integrated into guided interceptors for many missions.